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Field study on the thermal environment of passive cooling system in RC building

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Abstract

In recent years, various passive methods have come to be adopted in architecture design. The rooftop lawn is seen to have merit in the reduction in the air conditioning load of the building, as well as contributing to the mitigation of the heat island phenomenon. The roof spraying system is seen to be an effective method for the roof of low heat insulation performance, and can greatly reduce the heat load in the summer season.

However, at present most of the buildings with an RC construction have the insulating material in the roof for providing thermal insulation in the winter season. There has been a trend to adopt the roof spraying system actively in even such a general RC building, but it is not clear how much actual effect it has.

In this study, the authors conducted a measurement in an RC building with a rooftop spraying system and roof lawn in order to clarify the effects and problems on the thermal environment.

Keywords: RC building; Roof spraying; Rooftop lawn; Thermal environment; Effect; Energy conservation

1. Introduction

In recent years, environmental problems have become serious, and various passive methods have come to be adopted in architecture design. The rooftop lawn is seen to have many merits such as; reduction in the air conditioning load of buildings and contribution to the mitigation of the heat island phenomenon. The roof spraying system is seen to an effective method for the roof of low heat insulation performance, which can reduce the heat load in the summer season.

In earlier research on rooftop spraying system, Hasegawa [1] carried out an analysis on the thermal effect of spraying system on slant roof. Shukuya [2,3] has done a field study on a rooftop spraying system.

The effect of roof spraying has been shown to contribute to the decline of room temperature certainly in the summer season, especially in the buildings with low heat insulation performance. However, at present most of the buildings have the insulating material in roof to effect the thermal insulation in the winter season. There has been a trend to adopt the roof spraying system actively in even such a general RC building, but it is hardly clarified how much actual effect it has.

Regarding the rooftop lawn, Ishihara et al. [4] had an experimental study on thermal characteristics and water performance of rooftop lawn. On the other hand, Hoyano et al. [5] had clarified the indoor thermal control effect of rooftop lawn planting with thin soil layer on a wooden building. There are few studies on the thermal environment in RC building.

In this study, the authors conducted a measurement in a RC building with a rooftop spraying system and roof lawn in order to clarify the effects and problems on thermal environment. The studied building is an office building, at the Advanced Research Institute of Science and Engineering, Waseda University, which is located in the Kitakyushu Science and Research Park.

2. Outline of the measurement

2.1. Outline of the studied building

The studied building has adopted various methods such as rooftop lawn and roof spraying system, to try to create

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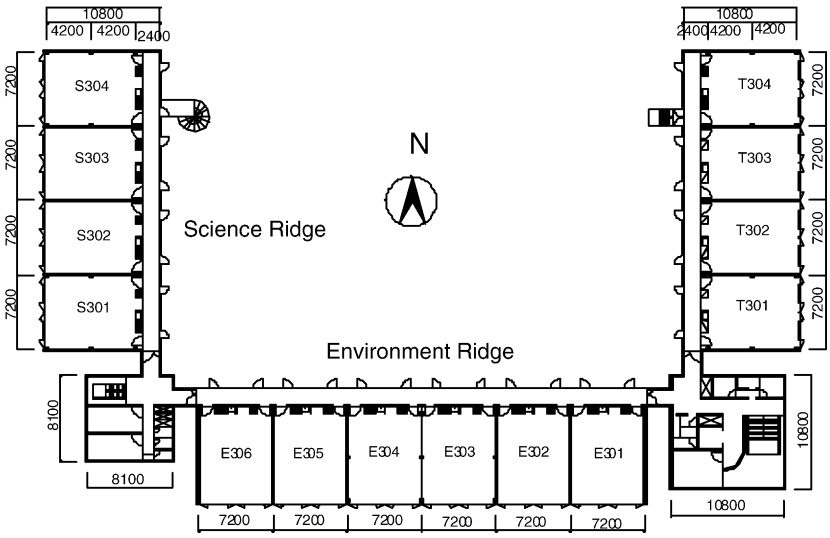


Fig. 1. The plan of measurement floor.

a green architecture. Fig. 1 shows a plan, which is a typical arrangement of office buildings. Enclosing the courtyard, it is composed of the buildings of the three ridges and three-storied, and it is one side corridor style plane constitution (Fig. 2).

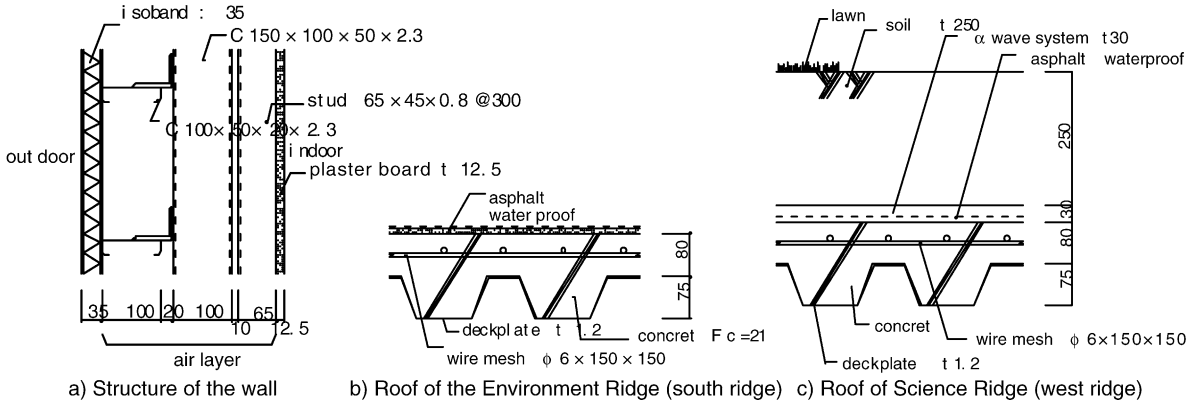
The building is used as experiment and research laboratory for Waseda University. The ridge facing south (for Environment Department) has adopted a rooftop lawn. The other two ridges on the east and west are for the Science Department; these have an automatic spraying device in the rooftop. The structure is shown in Fig. 3, it is an iron frame structure. The roof of ridge facing south is covered with a soil layer of 250 mm.

Fig. 2. Building appearance.

2.2. Measurement periods and place

From 15 to 17 August 2001, the authors carried out measurements on the third floor of the studied building. Figs. 4 and 5 shows the third floor plan and measurement point. For the measurement of roof spraying, we did it in the ridge of the west side (west ridge).

Though there were four rooms on the third floor, in order to remove the influence of outside air, the two middle rooms S302 and S303 were chosen for roof spraying. Measurement of the rooftop lawn was done in the room E305 of Environment Department (south ridge).



a) Structure of the wall b) Roof of the Environment Ridge (south ridge) c) Roof of Science Ridge (west ridge)

Fig. 3. The structure of the wall and roof.

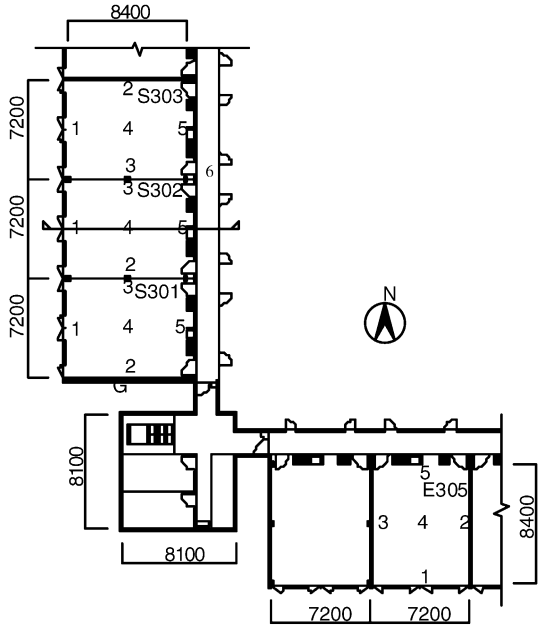


Fig. 4. The measurement point in plan.

The material of windows of each room are glass in the top two-third and aluminum in the bottom one-third. There are two doors in both corners of the wall on the corridor side. There are windows of full-scale glass in the corridor as well. To isolate the effect of only rooftop lawn and the roof spraying, all other elements are moved, all windows and doors were closed in three rooms as well, and all the windows of the corridor were closed too. All rooms were empty of occupants.

2.3. Measurement method and arrangement

An automatic water device sprinkler is installed on the roof of the west ridge, but because the volume of water was small, so we added water spraying manually. We sprayed continuously with a hose to keep it in the condition that the surface of the roof was always wet. Equally, confirmed and recorded the quantity of water every hour. Table 1 shows the amount of sprayed water from 09:20 until 17:00, on the 15th, by the same point, sprayed water during 12:00–17:00 on 16th, and during 10:00–17:00 on 17th.

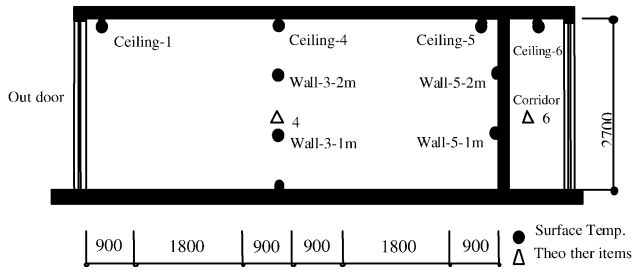


Fig. 5. The measurement point in section.

Table 1
Quantity of spraying

Time	Quantity of spraying (ℓ)
09:15–10:15	229
10:15–11:15	182
11:15–12:15	313
12:15–13:15	319
13:15–14:15	158
14:15–15:15	154
15:15–16:15	154

Measurements were taken on all four sides of each room and in the center of the room. The point of the window side, the center, the corridor side, the south wall and the north wall was made as points 1, 4, 5, 2 and 3, which were shown in the Table 2 and Figs. 4 and 5.

Indoor air temperature was measured in two places (center and corridor side). Humidity and globe temperature were measured in center of the rooms. Ceiling surface temperatures were measured in five places (center and the four corners of ceiling). Wall surface temperatures were measured in six places (1 and 2 m from floor on all walls except window side). The surface temperature of the floor and air velocity at the center of the room was measured.

The air temperature, velocity and surface temperature outside were also measured.

Room S302 had water spraying and the room S303 did not. In order to observe the effect of water spraying more clearly, and comparing the difference between two rooms, all doors and windows were closed to keep conditions similar in both rooms. The effect of air velocity is not discussed in this paper.

Table 2 lists the data collected. Data logs were kept automatically at 10 min intervals.

This paper concentrates on the data on the 17th because the effect appears most clearly here.

3. Results and discussion of measurement

3.1. Solar radiation

As shown in Fig. 6, the quantity of solar radiation from 15 to 17 August was greatest from 12:00 to 13:00, and the

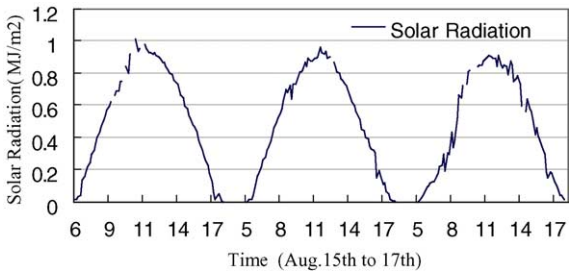


Fig. 6. Solar radiation during the survey period.

Table 2
Measurement items and method

Items	Points		Used devices	Detail
Room temperature	Center of each room and corridor	4, 6	Thermo Recorder RH, Cooper Constant	(1) Thermo Recorder RH (T&D. TR-72) (2) Copper Constant T-type 0.3 mm
	Side of each room	5		Copper Constant 0.3 mm
Room humidity	Center of each room	4		Thermo Recorder RH (T&D. TR-72)
Surface temperature	5 points of ceiling and 1 point for corridor	1, 2, 3, 4, 5, 6	Copper Constant	T-type 0.1 mm
	Floor	4		
	Wall	2, 3, 5	Anemo-Thermometer	T-type 0.3 mm
Air velocity	Center of each room	4, 6	Anemo-Thermometer	Anemo-Thermometer (AM-05)
Glove	Center of each room	4, 6	Glove Copper Constant	
Outdoor temperature and humidity	Outdoor		Thermo Recorder RH Cooper Constant	(1) Thermo Recorder RH (T&D. TR-72) (2) Copper Constant T-type 0.3 mm
Wind velocity	Outdoor			RION ANEMOMETER (AM-09T)
Surface temperature of roof	2 points of each ridge		Cooper Constant	T-type 0.1 mm
Recorder device	West ridge South ridge		Dataloga	(1) Tokyoskokki DATALOGA (TDS-601) (2) AUTOMATIL SWICHING BOX (ASW-SOC)

quantity on 15th exceeds 1 MJ/m^2, exceeds 0.96 MJ/m^2 on 16th, exceeds 0.88 MJ/m^2 on 17th. All days were almost clear throughout the survey period.

3.2. Exterior temperatures and relative humidity

Fig. 7 shows the air temperature and the relative humidity.

On the 15th, the outdoor air temperature became highest at 17:00, and the temperature was 36.8 °C. On the 16th, the lowest temperature was 26.5 °C at 06:00, the highest temperature was 35.3 °C at 12:00, and the daily temperature range was 8.8 °C. On 17th, the lowest temperature was 25.2 °C at 06:00, the highest temperature was 34.2 °C at 14:00 and the daily range was 9 °C.

On the other hand, the lowest relative humidity was 43.6% at around 17:00 on 15th, the highest relative humidity on 16th was 81.6% at around 06:00, when the lowest relative humidity occurring at 12:00 at about 39.8%. The highest relative humidity on 17th was 89.2% at around 06:00, when the lowest relative humidity occurring at 13:30 at about 46.8%. The daily range was 41.8% on 16th, 42.4% on 17th.

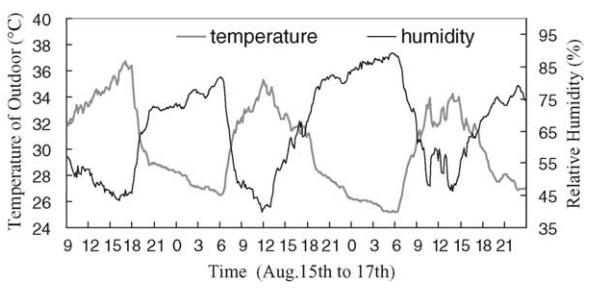


Fig. 7. Outdoor temperature and relative humidity.

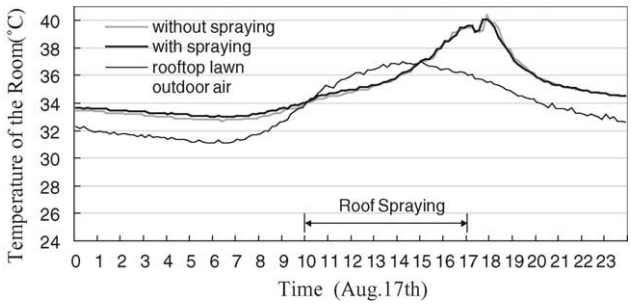


Fig. 8. The indoor air temperature.

3.3. Temperatures and relative humidity of indoor

The analysis of temperature and relative humidity of indoor was collected from the center of the room. Fig. 8 shows each room's temperature, Fig. 9 shows the relative humidity, Fig. 10 shows the temperature of the corridor.

3.3.1. Rooms with rooftop lawn (E305)

As shown in the Fig. 8, the daily temperature range was 5.8 °C on 17th, the lowest temperature was 31.2 °C at

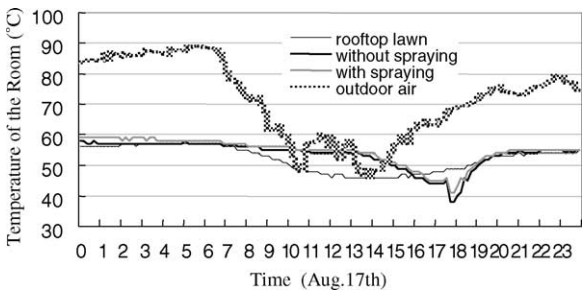


Fig. 9. Indoor humidity.

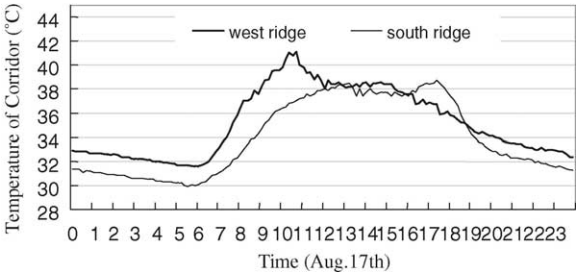


Fig. 10. Corridor temperature.

around 06:00–07:00, the highest temperature was around 36.5–37 °C from 13:00 to 15:00, the daily temperature range was 5.3–5.8 °C.

Regarding the relative humidity of indoor, on 17th, it was kept 57% from 00:00 to 07:00, and became lower from 07:00, the lowest was 46% from 13:00 to 14:00. The daily range was about 11%.

The outdoor air temperature change was extreme, while the indoor temperature remained stable compared with the outdoor. The humidity level of the room with rooftop lawn was also lower than that of the outdoor. Therefore, it can be said that the rooftop lawn can mitigate the maximum air temperature and as a result, provide a good thermal environment.

3.3.2. Room without roof spraying

As shown in the Fig. 8, on 17th, the lowest temperature was 32.7 °C at around 06:00, the highest temperature was around 40.4 °C at 17:50, and the daily temperature range was 7.7 °C.

Regarding the relative humidity of indoor on 17th, it was kept 57% from 00:00 to 06:00 and became lower from 07:00, the lowest was 38% at 17:40. The daily range was from 15 to 19%.

3.3.3. Room with roof spraying

As shown in the Fig. 8, on 17th, the lowest temperature was 33 °C at around 06:00, the highest temperature was around 40.1 °C at 17:50, and the daily temperature range was 7.1 °C.

Regarding the relative humidity of indoor on 17th, it was kept 59% from 00:00 to 06:00 and became lower from 07:00, the lowest was 41% 17:40. The daily range was 16–18%.

3.3.4. Corridor

As shown in Fig. 10, regarding the corridor of the south ridge where there is a rooftop lawn, the lowest temperature was 29.9 °C at around 5:30, the highest temperature was around 38.7 °C at 17:20, and the daily temperature range was 8.8 °C.

Corridor of the west ridge was influenced by the morning sunshine, the lowest temperature was 31.6 °C at around 05:30, the highest temperature was 41.1 °C at 10:40, and the daily temperature range was 9–14.6 °C.

3.3.5. Comparison

As shown as Fig. 8, compared with the other two rooms, the temperature of the room with the rooftop lawn was relatively stable. Also, it continued low during the afternoon, although the temperature is higher than the other two rooms in the morning. The highest temperature appears early, but it became constant and fluctuation became gradual during daylight. On the other hand, in the room without a rooftop lawn the temperature goes up sharply during the afternoon, the highest temperature was 3–4 °C higher than the room with rooftop lawn. The peak temperature is delayed as long as 4 h in the room with the rooftop lawn until it reaches the highest temperature, and it was observed that the temperature went up sharply under the influence of the afternoon sun.

There was little temperature difference between the room with the spraying and the room without the spraying. It was observed that the effect of spraying water did not affect room temperature. This result from RC building seems to be dependent on the room's highly insulated ceiling material.

3.4. Indoor surface temperature

3.4.1. The ceiling

To observe the effect of the roof spraying and the rooftop lawn, we studied the ceiling surface temperature. The study used the mean value of the measurement point of five points. The fluctuation of ceiling surface temperature resembles room temperature.

3.4.1.1. Rooms with rooftop lawn. As shown in Fig. 11, The lowest temperature was 31.4 °C at around 06:00–07:00; the highest temperature was around 36.2 °C at 15:00.

3.4.1.2. Room without roof spraying. As shown in Fig. 11, The lowest temperature was 33.1 °C from 06:00 to 08:00; the highest temperature was around 38.1 °C at 17:10.

3.4.1.3. Room with roof spraying. As shown in Fig. 11, The lowest temperature was 33 °C from 06:00 to 08:00; the highest temperature was around 37.8 °C at 17:00.

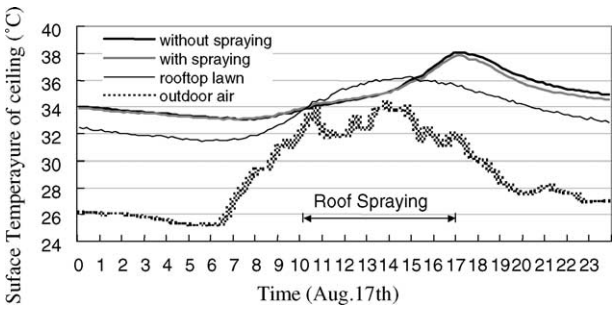


Fig. 11. Ceiling surface temperature.

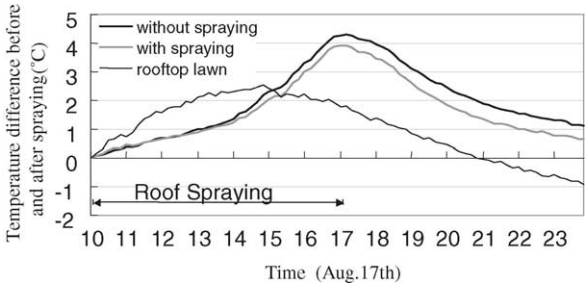


Fig. 12. Difference between before and after spraying.

3.4.1.4. Comparison. The surface temperature of ceiling of the room with the rooftop lawn remained stable compared with the other two rooms, and its maximum temperature was 3.5 °C less than in the other two rooms.

On the other hand, in the case of the two rooms without rooftop lawn covering (temperature, as shown as the Fig. 12), with the range of the temperature rise, the average ceiling surface temperature of the sprayed roof room was 0.3 °C less than the non-sprayed roof room.

And also, the difference increases gradually on the third day by spraying. This resulted from the heat capacity effect of the roof. This is to suggest that the effect of the spraying was turning up little by little.

The fluctuation of the ceiling surface temperature resembles the indoor air temperature; the room with rooftop lawn remains stable compared with the other two rooms. In the case of the two rooms without rooftop lawns, west ridge temperature fluctuated sharply.

3.4.2. The wall and the floor

Wall surface temperatures were measured 1 and 2 m above the floor. The results appear in the Figs. 13–15. The temperature of the wall of the corridor side was highest in each room, and the sidewall temperature was almost the same. The surface temperature was higher in accordance with the height for the same wall, and the difference was about 0.2 °C. From Figs. 13–15, it is seen the temperature increases from floor, wall, to ceiling.

There was no difference with the two rooms of west ridges, but the wall temperature of the room with rooftop lawn was 1–1.5 °C lower.

As shown in Fig. 16, the temperature of the floor with the rooftop lawn lowered gradually, and on the 17th, it was even

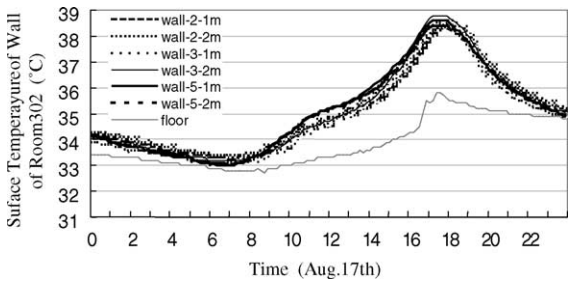


Fig. 13. Wall surface temperature of room 302.

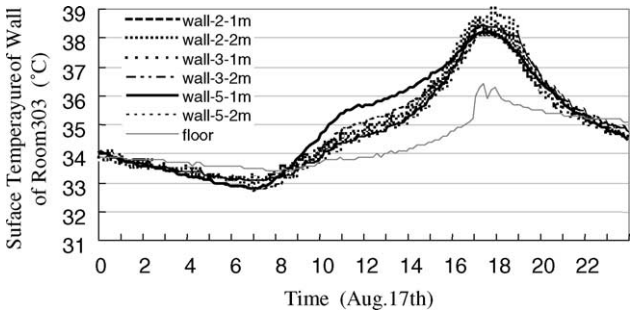


Fig. 14. Wall surface temperature of room 303.

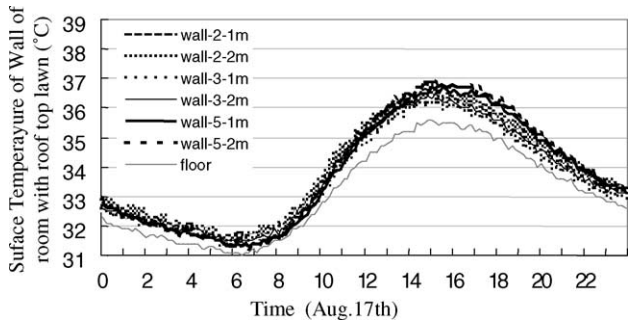


Fig. 15. Wall surface temperature of room 309.

lower than the room without the rooftop lawn. Furthermore, the room with the rooftop lawn had carpet floor while the rooms on the west ridge did not.

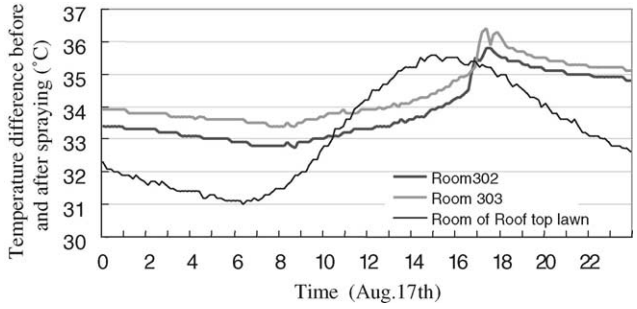


Fig. 16. Floor surface temperature.

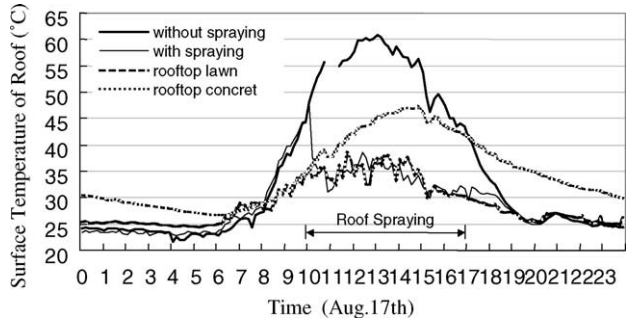


Fig. 17. Roof surface temperature.

3.5. Surface temperature of roof

Fig. 17 contains information on the surface temperature of the roof. The roof temperature without spraying water became lowest at 04:00, it was 21.6 °C, and the highest temperature was around 60.8 °C at 13:00. On the other hand, the roof with spraying water became the lowest temperature was 22.8 °C at 04:10, before spraying it reached 48.3 °C, but when beginning spraying water at 10:00, it was kept 37.5 °C, and became highest at 00:20 without exceeding 39 °C.

Regarding the roof of south ridge, the authors have measurement for two points, one was the concrete surface along the corridor, and the other was the lawn on the room. The temperature of the concrete was fluctuating from 27 to 48 °C during the 3 days, and the lawn was fluctuating from 25 to 37 °C, remaining relatively stable.

The rooftop temperature varied in accordance with their composition: The west ridge, with its spread prevention sheet, was 13 °C lower in temperature than the other roofs which were concrete.

3.6. The effect of spraying on surface temperature of roof and ceiling

Fig. 18 shows the temperature difference of roof and ceiling between rooms with and without roof spraying water. The ceiling temperature difference between two rooms is shown in the second column because it is so small.

Before the application of roof spraying water, the roof surface temperature of the two rooms is the same. When spray begins, the ceiling surface temperature of the room that sprayed fell down greatly. The temperature difference became biggest from 11:00 to 15:00. The temperature was 20–25 °C. From 15:00, the difference was reduced and almost became the same again after the spraying water stopped.

On the other hand, the ceiling surface temperature difference was not so much for a while. Even after spraying started, the room with spraying ceiling surface temperature was much higher at the beginning.

After spraying water the temperature fell gradually. The difference between two rooms increased even after spraying stopped. It become biggest at 20:00, 3 h after spraying

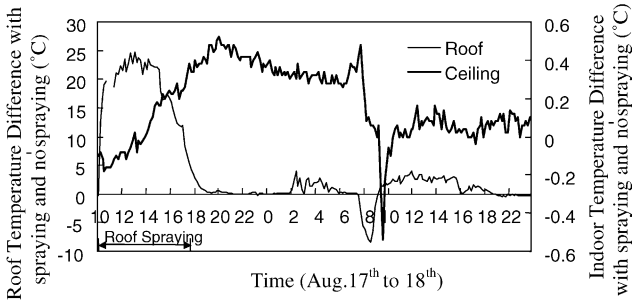


Fig. 18. Temperature difference of roof and ceiling.

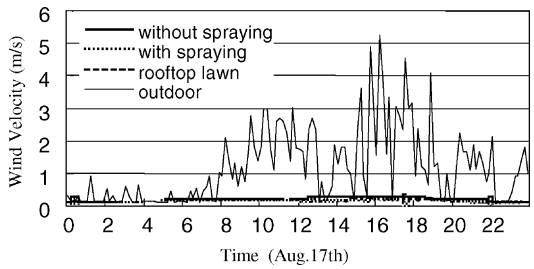


Fig. 19. Indoor and outdoor wind velocity.

stopped, the temperature was 0.5 °C. The peak time appears delayed for 7 or 8 h from the peak time of roof surface temperature difference. And after spraying stopped, the difference was retained all night until 08:00 of the next morning.

The effect of spraying appears very late, but be in effect for a long time. It is considered to be function of the insulation efficiency of the RC building.

3.7. Wind velocity of indoor and outdoor

Regarding the outside wind velocity, ranged from 0.1 to 5.5 m/s with average of 1.4 m/s, while there was almost no wind velocity indoors. Fig. 18 shows the results.

4. Conclusions

In this research, the authors through their analysis have clarified the effect of rooftop lawn and roof spraying, in a building with RC construction and high thermal insulation. The effect of the roof spraying is seen to some extent, but it is difficult to say that it contributed to the reduction of the heat environment load because the roof insulation of high factors in the roof. Considering how much water had to be sprayed, it is hard to say that water spraying can save energy. Our conclusion is that roof spraying is not suitable for an RC building with a high degree of insulation in the roof. On the other hand, the rooftop lawn had good characteristics in stabilizing the indoor environment where the lowest temperature obtained at nighttime. It mitigated and restrained the maximum air temperature of the daylight, and also helped in mitigating the heat island phenomenon. The rooftop lawn is an effective passive method and is also adaptable to many buildings (Fig. 19).

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References

[1] T. Hasegawa, Y. Konna, A study on improvement of the thermal environment in a large building with folded roof deck plate. Part 4. Temperature of a drop of water from the watering nozzle and surrounding air in the open air, in: Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan, 2001, pp. 473–474.

[2] T. Tanabe, R. Sayama, H. Saito, et al., Measurement of the effect of a change in slate-roofing from single to double with water spraying on lowering the ceiling surface temperature, in: Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan, 2000, pp. 507–508.

[3] H. Saito, R. Sayama, T. Tanabe, et al., Qn energy analysis on the shading effect of doubled-slate roofing with water spraying, in: Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan, 2000, pp. 509–510.

[4] O. Ishihara, Q. Zhang, K. Shimoyama, Experimental study on thermal characteristics and water performance of rooftop lawn, Journal of Architectural Planning and Environmental Engineering 484 (1996) 17.

[5] A. Hoyano, K. Shirai, N. Otsuka, K. Iwamura, Indoor thermal control effect of rooftop lawn-planting with thin soil layer on a wooden building, Journal of Architectural Planning and Environmental Engineering 527 (2000) 15.